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Multi-Images of Weathered Stones of Monuments

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IMAGE SEGMENTATION APPLIED TO SCANNING ELECTRON MICROSCOPY
MULTI-IMAGES OF WEATHERED STONES OF MONUMENTS

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Abstract

This paper describes a three complementary images processing method. The three images are coming from a scanning electron microscope (SEM) during the analysis of a particular stone: the Tuffeau used in most monuments of the Loire valley (France). The goal is to separate two classes of particles (calcareous and siliceous) from the porosity to give more information to experts who evaluate the damage of weathering on monuments. A specific process is developed: a first threshold on the good quality image allows separation of particles from porosity. Then, the complementarity of the three images gives the two other thresholds. Granulometry, percentages of components, and anisotropy of the porosity are precious information that can be derived from the three segmented image.

Key Words: Tuffeau stone, weathering, scanning electron microscope, image processing, image segmentation, histogram, thresholding, historical monuments, weathered stones.

Introduction

Weathering is a severe problem in the preservation and conservation of historical monuments. The stone, in the architectural environment, is exposed to numerous types of attack; the most important damage results from monument surfaces being in contact with the atmosphere. Polluted rain water, especially rich in acids or active gas molecules, results in a chemical attack of the stone.

The aim of this paper is to present some ways of using image analysis to improve the study of the alteration of the most widely used stone of the Loire valley: the Tuffeau. For these, the problem is exacerbated by the porosity of the stone (between 20 to 50% in volume) which implies that they have a high specific surface. Besides porosity, we find that little particles and material (containing either calcium or silicon particles) as well as poorly defined forms, such as gels and colloids, are also present.

Some difficulties appear during studies of the granulometry and porosity of these samples due to the small dimension of the particles and the poor definition of some classes (Rautureau and Pierre, 1991). With the scanning electron microscope (SEM), the spatial resolution is better than with the optical petrographic method especially in these cases of very small particles (Rautureau, 1990). From a petrographic slice of the Tuffeau, three complementary SEM images are obtained: a backscattered electron image, two X-ray elemental maps (one for silicon and one for calcium). Image segmentation is complicated by the poor quality of the signal at particle interfaces. The signal-to-noise ratio is low especially in the case of element mapping by X-ray spectral analysis. So, an adapted strategy of segmentation is developed: first the threshold on the electron image allowing separation of porosity from particles. Then, the complementarity of the images permits determination of the two other thresholds to separate calcium particles from silicon particles. Basic results with some complementary studies lead to a knowledge of various parameters concerning porosity, percentage of components, anisotropy and granulometry (Harba et al., 1991). These results shed light on the mechanical and chemical
reactions, and behavior of the stone.

**Description of the Tuffeau**

Tuffeau is a detritic polyphase material of the Turonian stage. It is located in France, essentially in the Loire valley, where many cathedrals, castles and private houses are constructed with this stone. Its composition varies widely but it always contains calcite and silica as major components, plus some mica (composed of silicon). Other minerals, less than 2%, appear essentially as oxides and sulfides (Rigo, 1990). The main property of Tuffeau is its high porosity associated with small dimensions of detritic particles. Inside the pores, we found very few submicron particles and colloids of nanometric dimensions which could only be observed in transmission electron microscopy images. The polyphase character and the division of the Tuffeau give it a high specific surface of 23 m²/g which explains the surface and interfacial properties appearing during observations especially for particle analysis. Samples are impregnated with resin to form petrographic sections with a standard thickness of 30 µm. The SEM observations are made perpendicular to the polished surface at 25 kV with backscattered electrons and X-ray elemental maps. In the present case, a low magnification is sufficient to correctly describe the granulometry of the materials.

The polyphase character associated with the low electrical conductivity of the sample prevents physical studies of the electron diffusion, and under these conditions, the resolution, though not the best, is sufficient to give a satisfactory image definition of the particles. The quality of the information is limited by photographic acquisitions on a Polaroid film and by the digitization of the films. Digitization is performed with a charge-coupled device (CCD) camera whose aperture is kept at its optimum: 8. The numerization process is made with a PIP 1024 Matrox frame grabber at a format of 256*256 pixels. The pixel size is about 1.5 µm and the smallest particles are about 5 µm. The gain and offset were set in order to have a correct histogram, with no saturation at the highest intensity, as shown in Figures 1b, 2b and 3b (the peak at 127 on the histograms is due to a default of the frame grabber).

A backscattered electron image is shown in Figure 1a and its grey value histogram is presented in Figure 1b. A close inspection to the electron image and its histogram shows that the Tuffeau can be easily split in two: particles (left part of the histogram and in black on the image) and porosity. But a closer inspection can lead to the conclusion that each of the two distributions are again composed of two or three others. It would be unsatisfactory to try to separate calcium particles from silicon particles only with this information. Indeed, the black distribution could be separated in two: dark and very dark. But, calcium particles belong to these two sub-distributions. Moreover, they are very mixed so that a separation could not be performed without a lot of errors. Fortunately, X-ray analysis is possible so that calcium and silicon X-ray elemental maps can be obtained (Figs. 2a and 3a). The corresponding grey level histograms are presented in Figures 2b and 3b. As seen, the three images are complementary and related histogram bimodals, so that a threshold technique is justified. As mentioned previously, the best quality image is the electron one so that the following strategy is developed: a first threshold on the electron image (noted Te) separates porosity from particles. Then, the two other thresholds on the calcium and silicon images (respectively noted Tc and Ts) are determined using the *a priori* information of complementarity. Finally, we also have a knowledge about the errors made during the classification process.

**Selection Between Porosity and Particles**

In all the following formulae, \( p_i \) is the probability of occurrence of a pixel at a grey level \( i \), given by \( p_i = N_i / N \) where \( N_i \) is the number of pixels at a level \( i \) and \( N \) is the total number of pixels (in the present case 256*256, i.e., 65536). We used three different techniques among those described by Sahoo et al. (1988) to determine \( T_e \).

**a) Bayesian minimal error**

The probability \( p_i \) is considered to be the weighted sum of two normal distributions \( p(i)/j) \):

\[
p_i = \sum_{j=1}^{2} W_j \cdot p(i)/j),
\]

with

\[
p(i)/j) = \frac{1}{\sigma_j \sqrt{2\pi}} \exp \left(-\frac{(i-\mu_j)^2}{2\sigma_j^2}\right)
\]

where \( W_j, \sigma_j \) and \( \mu_j \) are to be determined. Then the threshold, splitting the distribution with the minimum error, can be easily found. Kittler and Illingworth (1986) proposed a simple method to iteratively find both the distributions parameters and the optimal threshold \( T_e \) in the sense of minimum error method. It can be briefly explained: choice of an arbitrary threshold as a starting point, computation of the distribution parameters, determination of an updated threshold which minimize the error due to the mixture. If the updated threshold is equal to the one chosen then stop the procedure, otherwise, take the updated threshold as a starting point until convergence.

**b) Maximum entropy method**

One can associate with an histogram an entropy function such as:

\[
E(P) = - \sum_{i=0}^{i=M-1} p_i \cdot \log_2(p_i).
\]

where \( M \) is the number of grey levels.
Image segmentation applied to weathered stones

Figure 1. Backscattered electron image (a) and its histogram (b).

Figure 2. Calcium X-ray map (a) and its histogram (b).

Figure 3. Silicon X-ray map (a) and its histogram (b).
The method proposed by Kapur et al. (1985), uses, after thresholding at a level $T$, two distributions, $B$ and $O$ (background and object), and their respective entropy can be defined, thus:

$$E(B) = \sum_{i=0}^{i=T} p_i \log_b \left( \frac{p_i}{p_T} \right)$$

and

$$E(O) = -\sum_{i=T+1}^{i=M-1} p_i \log_b \left( \frac{1-p_i}{1-p_T} \right)$$

with

$$p_T = \sum_{i=0}^{i=T} p_i$$

The maximum of the function $H(T) = E(B) + E(O)$ gives the best information and hence the optimal threshold $T_e$ in the sense of maximum entropy method.

c) Histogram modification

The basic idea is the following: the gradient function at a certain position in the image, called $\Delta$, is high at the boundaries between background and object. So, if the grey level of an image are weighted by a function of $\Delta$, the effects on the histogram will be a local modification corresponding to the optimal threshold in the sense of this technique. For example, if one chose this function to be:

$$\frac{1}{(1+|\Delta|^2)}$$

then, a "hole" will appear and therefore, the choice of the threshold will be trivial.

d) Comparison of the three methods

The three methods have been tested on a set of 11 electron images. For each image, an expert in Tuffeau chose an optimal threshold to split as well as possible particles from porosity. This was taken as a reference. Then the three methods were applied on this set of 11 images. An average gap between methods and expert opinion can be determined. This was 24, 21 and 41 grey levels for method $a$, $b$ and $c$, respectively. So, the maximum entropy method is finally chosen to obtain $T_e$.

Separation of Particles Types

The complementarity of the three images is used to separate the calcium particles from the silicon particles and yields $T_c$ and $T_s$. Imagine that an optimal threshold for each of the three images could be determined, then each pixel would belong to one and only one of the following classes: porosity, calcium, or silicon. But, in a practical case, some pixels belongs to no class, to two classes, or to the three classes. The optimal thresholds $T_c$ and $T_s$ (since $T_e$ is already fixed) in the sense of the superposition will be those such as the number of badly classified pixels will be minimum. So, a discriminating function sum of the badly classified pixels $D(T_c,T_s)$ at fixed $T_e$ is defined as follows (Harba et al., 1990):

$$D(T_c, T_s) = N_0 + N_{ps} + N_{pc} + N_{cs} + N_{pcs}$$

where
- $N_0$ are pixels which belongs to no classes,
- $N_{ps}$ pixels common to porosity and silicon,
- $N_{pc}$ pixels common to porosity and calcium,
- $N_{cs}$ pixels common to calcium and silicon,
- $N_{pcs}$ pixels common to porosity, calcium and silicon.

The best superimposition of the three views corresponds with the minimum of $D(T_c,T_s)$. So, the optimal threshold $T_c$ and $T_s$ in the sense of the superimposition as previously defined can be determined.

Results

Our strategy [called $D(T_c, T_s)$ as explained above; choice of $T_e$ then choice of $T_c$ and $T_s$ by minimization of the function $D(T_c,T_s)$], has been compared to other methods:
- separate thresholds on the three images by the minimum error method (called Min. Error),
- separate thresholds on the three images by the maximum entropy method (called Max. Entr.),
- separate thresholds on the three images by the histogram modification method (called Hist. Mod.).

Table 1 gives the threshold found by the four different methods on the set of three images presented in Figures 1, 2 and 3. For the porosity image, which is the best quality image, the thresholds are more or less identical (respectively 74, 98 and 104 for method $a$, $b$ and $c$ since for our method, $b$ has been chosen). But for the two other images, variations are very important. This justifies our strategy of first choosing the threshold on the electron image. Table 2 gives the number of pixels of each type for the four methods ($N_p$, $N_c$ and $N_s$ are the number of pixels of porosity, calcium and silicon areas, respectively) and also the number of badly classified pixels, $\Sigma bc$. As seen on the Tables, only our methods, as expected, give the smallest number of badly classified pixels, i.e., 14815. Other methods give, in the
best case, about 50% more badly classified pixels. Our method uses a priori information, and therefore, gives better results in terms of superimposition errors.

**Conclusion**

This paper describes a three complementary image processing provided by SEM analysis of a petrographic slice of the Tuffeau stone. The goal is to separate porosity from calcium particles and silicon ones. Image histograms being bimodal, threshold technique is well adapted. A specific method has been developed taking into account the image quality as well as their complementarity. First, the threshold on the good quality image (backscattered electron image) is determinate using a classical thresholding method. Then, the two other thresholds on the silicon and calcium X-ray images are found by the minimization of the badly classified pixels. Our method is compared with classical methods applied independently on each image and gives better results in terms of superposition errors. Following this, it would be possible to affect bad classified pixels to one of the three classes.

Once segmented, it would be possible to derive a lot of information which can be of a great interest to improve the expertise of the stone: the percentage of components allows to appreciate the degree of alteration of the stone (less calcium means a more fragile stone), the anisotropy of the porosity shows the layers (useful in case of a stone replacement), the granulometry put in sight the average size of the particles (a small average particle size indicates a strong stone).

Other methods taking into account the a priori information of complementarity are possible (i.e., local segmentation). But our technique is very simple, works well and can be implemented in real time on a SEM.

**References**


**Discussion with Reviewers**

P. Smart: Can the thresholds derived analytically be related to a visual assessment of the histograms?

Authors: Yes, they are separating the histograms in two parts in the "flat" zone of the histogram.

P. Smart: Could the Bayesian method be improved by using a Poisson distribution (see Figs. 2b and 3b)?

Authors: Sometimes it could be better and sometime not depending on the shape of the histogram.

P. Smart: In Table 2, the discriminating function for Max. Entr. is 21777 and that for His. Mod. is 21056. These values are very similar, yet the values for Ne and Ns are very different. Could the authors comment on this point?

Authors: This is just a coincidence.

P. Smart: Could a multi-variate method of segmentation be used? For example, if p = pores, c = calcite, and s = silica, would it help to rescale the data so that

\[ p + s + e = 1; \]

then test its accuracy by:

\[ e = 1 - p - c - s, \]

where e is the error at a pixel; then map pores by

...
thresholding: \( (p + 1 - c - s) / 2 \)

**Authors:** Yes, but the problem is the noise on X-ray images.

**G. Bonifazi:** The authors clearly describe the procedures adopted and the hypothesis assumed at the base of each segmentation procedure, but there is no mention about the possibility to adopt an other strategy for segmentation, different from "histogram analyses"; as for example, a pre-processing procedure to enhance the image and an "image survey" in order to identify on the image itself areas characterized by local variations, minima or maxima, representative for example of different mineral phases or, with reference to this work, phases or porosity. Why have the authors followed this way (histogram analysis) and not the other (image enhancement and direct area identification)? How long is the procedure adopted and what are, from a practical point of view, the difficulties arising using such a procedure? Can the different analytical steps be easily automated?

**Authors:** No preprocessing is done to enhance the image (it is only a visual effect as for histogram equalization). The reduction of noise, mostly in X-ray images due to the SEM, would be difficult in our case. First, a very good knowledge of this specific noise (a "spot" noise plus a white noise) would be necessary and then, specific method should be developed if possible.

The detection of minima-maxima in the three different images has been thought as a possibility. This was not chosen because of the bad quality of the X-ray images and especially because of the noise. Another strategy, an extension of the relaxation method in our particular case (Harba R, Jacquet G. An extension of the relaxation method to a set of multi-sources images. GRETSI Conference, September 1991, Juan les pins, France, p. 16-20), has also been developed. But the strategy we have developed (a first threshold on the electron image and then threshold on the two X-ray images by minimization of the number of bad classified pixels) gives the best results.

**G. Bonifazi:** The acquisition of the image sample by a CCD camera produce, as correctly reported by the authors, a loss of information. Have the authors tried to quantify this reduction of information? What kind of analytical image analysis system has been used?

**Authors:** As long as the Shannon frequency is respected for the digitization process, no information is lost. In our case, the smallest particles are about 5 pixels. For the present case, a specific software has been developed by us at the University of Orleans.

**G. Bonifazi:** The methodology described produces, as output, a set of segmented images containing information about porosity of Tuffeau. The images are then examined by an expert in order to derive information about the alteration status of these rocks. Have the authors thought to implement an automated image processing procedure to analyze and numerically quantify the morphometry and morphology of grains and porosity, in order to give to the expert additional information about the micro-status of the rock? What kind of morphological analyses (Fourier shape analysis, fractal approach, mathematical morphology) do they plan to eventually implement in order to realize a better characterization?

**Authors:** We have not developed specific process along the lines you suggest. As stated in the conclusion, the percentage of components, the granulometry of the particles (through mathematical morphology) have been developed. Moreover, the anisotropy of the porosity has been done (Harba et al., 1991).

**N.K. Tovey:** Noise is a problem in the X-ray images and this can affect the thresholding techniques. Would this problem become even more acute if more than three phases are present?

**Authors:** If \( N \) phases were present, \( N + 1 \) images would be necessary. Unclassified pixels are mostly present at the particle interface, generally due to noise. Hence, the more images, the more interfaces, so that the number of poorly classified pixels would increase.

**N.K. Tovey:** Have the authors considered adapting either the "supervised" and "unsupervised" multispectral techniques commonly in use in remote sensing?

**Authors:** Because of time constraints, we prefer a dedicated and specific method. We do not have access to the remote sensing method in our own laboratory, but it is evidently possible to adapt these programs for electron microscopy. We regret that we cannot give a more precise answer to this question.